Environmental and childhood lead contamination in the proximity of boat-repair yards in southern Thailand—I: Pattern and factors related to soil and household dust lead levels

Nipa Maharachpong, Alan Geater*, Virasakdi Chongsuvivatwong

Epidemiology Unit, Faculty of Medicine, Prince of Songkla University, Songkhla 90110, Thailand

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Abstract

High blood lead levels have recently been documented in schoolchildren living in communities adjacent to boat-repair yards in southern Thailand. In this study, the spatial pattern of lead contamination of soil and household dust in an area surrounding several boat-repair yards is described, and household factors associated with elevated dust lead are identified. A cross-sectional spatial study was conducted in a coastal residential area within a distance of 2 km from three major boat-repair yards situated on the east coast of peninsular Thailand. Household dust specimens were collected from an undisturbed position in the residences of children, aged 4–14 years, sampled randomly from all children living in the study area. Soil specimens were obtained from the interstices of a square grid, $70 \times 70\,m^2$, superimposed on the area. Geographic coordinates of residence and soil sampling positions were recorded and semivariograms and kriging used to contour the spatial distribution of lead in dust and soil. Environmental lead levels were also modeled in terms of direction and minimum distance from a boat-repair yard and, for household dust lead content, in terms of household variables, including occupation of household members in boat-repair work, type of house construction, and general cleanliness. Household dust and soil lead content ranged from 10 to 3025 mg/kg and from 1 to 7700 mg/kg, respectively. The distribution of soil lead peaked at the location of the boat-repair yards, but outside the yards the distribution was generally below 400 mg/kg and irregular. About 24% of household dust lead specimens were equal to or above 400 mg/kg, but showed significant decrease with increasing distance from the boat-repair yards, at rates of between 7% and 14% per 100 m. In houses where a family member was a worker in one of the major boatyards and in houses where occasional repair of small boats was undertaken, household dust lead levels were significantly elevated, by 65% (95% CI: 18–130%) and 31% (95% CI: 5–63%), respectively. Siting of boat-repair yards at a distance from residential areas and measures to reduce the spread of lead-containing dust are recommended to alleviate the problem of elevated household dust lead levels.

Keywords: Dust lead; Soil lead; Spatial analysis; Boat repair; Thailand

1. Introduction

Lead contamination of surrounding environments and communities has been reported in association with the degradation of lead ore (Gulson et al., 1996a; Spear et al., 1998; Steele et al., 1990), smelting of lead (Galvin et al., 1993; Hertzman et al., 1991; Maravelias et al., 1989), the manufacture of lead batteries (Gartside et al., 1982; Ibiebele, 1994; Lee, 1982), the use of lead-containing paint (Bates et al., 1995; Booher, 1988; Laxen et al., 1987), lead water pipes (Quinn and Sherlock, 1990) and leaded gasoline (Billick et al., 1980; Fergusson and Schroeder, 1985; Tera et al., 1985), and with battery dumps (Matte et al., 1989) and mining waste dumps (Arykul and Kooptarnon, 1993; Geater et al., 2000). The principal routes of lead contamination in humans are via the digestive tract and respiratory system and, for organic lead compounds, absorption through the skin. Soil and dust lead have been identified as the most significant contributors to lead exposure in humans in a number of different settings (Adgate et al., 1995; Duggan, 1983; Hibbert et al., 1999; Jin

*Corresponding author. Fax: +66 74 212900.
E-mail address: alan.g@psu.ac.th (A. Geater).

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et al., 1997; Murgueytio et al., 1998). Unintended ingestion is the major pathway of exposure to lead in soil and dust, especially in young children (Garcia Vargas et al., 2001; Lorenzana et al., 2003; Rahbar et al., 2002).

A more recently identified source of lead contamination is the wooden-boat-repair industry. In southern Thailand, high levels of blood lead in children in a coastal community were found to be associated with residence close to a boat-repair yard. The process of building and repair of wooden boats involves the use of plumboplumbic oxide (Pb_3O_4) as a component in the caulking mixture applied between the planks of the hull (Geater et al., 2000). More than 200 wooden-boat-repair yards are situated throughout the coastal regions of Thailand (Department of Industrial Works, 2004) and many of these are located close to residential communities. Thus, this industry may pose a potentially serious and widespread threat to the health of coastal residents.

In spite of this potential for human and environmental contamination, few data are currently available on the extent of lead contamination of the environment adjacent to boat-repair yards. The study reported here is part of a larger investigation aimed at determining the impact of the boat-repair industry on environmental and childhood lead contamination levels. This part addresses the spatial distribution of lead in soil and household dust in the vicinity of boat-repair yards in a coastal region of southern Thailand. In particular, we were interested to determine the relationship between distance from a boatyard and environmental lead levels and to identify other household variables that might influence the lead content of household dust.

2. Materials and methods

2.1. Study site

The study site was located in Tambol Hua Khao, Singhanakorn District, Songkhla Province, at the mouth of Songkhla Lagoon on the eastern coast of southern Thailand, where three large yards for the repair of large wooden fishing boats are located (Fig. 1). Boatyard 1 reported repairing between 25 and 30 boats/month, boatyard 2 about 10 boats/month, and boatyard 3 between 15 and 20 boats/month at their busiest season. However, boatyard 2 had not been used to capacity in recent years. The three boatyards had been in operation for 21, 40, and 20 years, with work forces of 30–50, up to about 10, and 13–20 workers, respectively, actively engaged in boat repair, the precise number of workers at any time depending on the number of boats brought for repair.

Surrounding these boatyards are several residential communities of generally low socioeconomic status, which are served by three primary schools. Physical separation of the boatyards from the closely adjacent communities was substantial only in the case of boatyard 3, which was largely enclosed by a concrete wall: the other two yards were separated from the community only by incomplete and loose fencing, with access by the general public not particularly restricted. Common occupations among the communities included small-scale fishing, boat-repair work, small-scale trade, and unskilled labor. The habitable area formed a

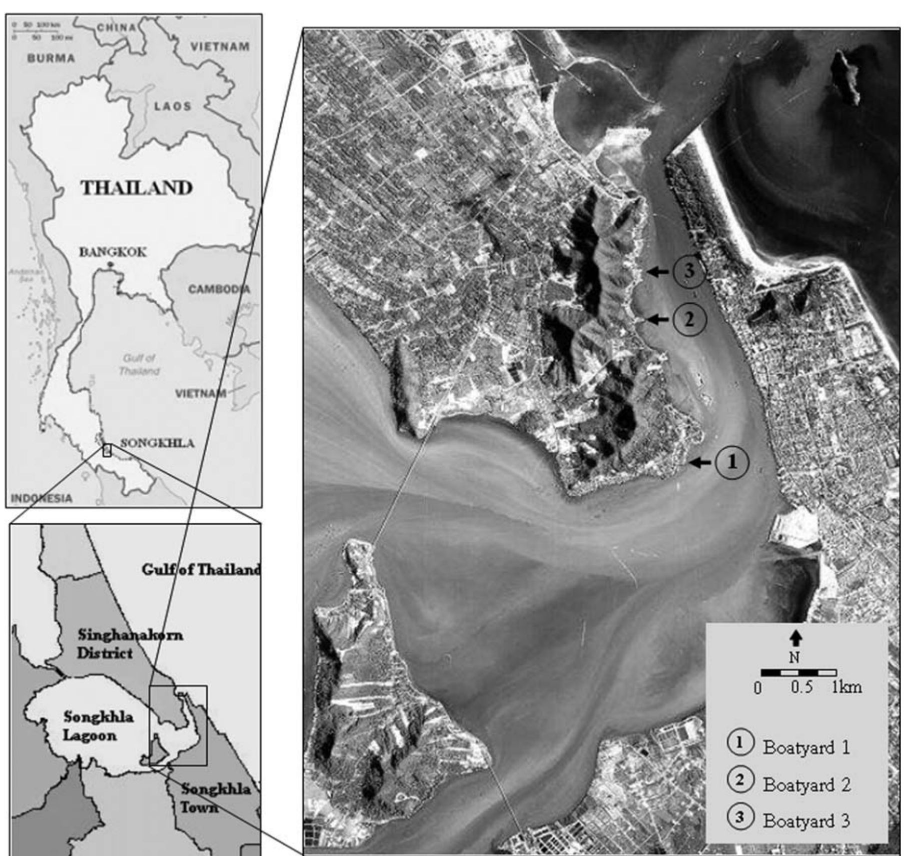

Fig. 1. Map of the study area, Hua Khao Subdistrict, Singhanakorn District, Songkhla Province, Thailand.

relatively narrow strip of land varying from approximately 50 to 300 m wide, running between uninhabited hills and the shore of the lagoon (Fig. 1). An approximately 6-km length of this land strip was selected as the study area. A single, narrow, partly paved road runs through the length of the study area and is used predominantly for local deliveries and by residents using motorcycles. Only a few residents own a car or pickup vehicle. Access to houses not located directly adjacent to the road was mostly via narrow paths wide enough for a motorcycle but not for a four-wheeled vehicle. The nearest urban center lies to the east across the mouth of the lagoon at between 1 and 3 km from the study area. Within the study area there were an estimated total of 1400 households and 895 children between the ages of 4 and 14 completed years.

This setting of boat-repair yards, with closely adjacent relatively poor communities, is similar to that in several other coastal provinces of southern Thailand.

In this study area, in addition to boat-repair work in the three boatyards, a number of households located at the edge of the lagoon throughout the area undertake repair of small wooden boats at home, using the same or a similar technique involving plumboplumbic oxide in the caulking mixture as in the boatyards.

2.2. Sampling and analytical methods

2.2.1. Household dust specimens

Households included in this study were the residences of 319 children selected for the larger study of childhood and environmental lead contamination. The children were selected by simple random sampling from combined lists from the three local schools of all children aged between 4 and 14 completed years resident in the local community whose homes were situated within 2 km of any one of the three boat-repair yards. The 319 children belonged to 242 households.

A visit was made to each of the 242 households in March and April 2001 to collect a dust specimen. To obtain an estimate of the level of lead in household dust over a prolonged period, specimens of dust were obtained from little-disturbed places at least 1.5 m above the floor of the main living area, such as the tops of doors/window sills, ventilation holes, or the tops of wardrobes. Dust was collected by brushing lightly with a new toothbrush onto a clean paper sheet and then transferring the dust to a new clear polyethylene bag for subsequent determination of dust lead content in units of weight of lead per weight of dust. Dust specimens from at least two places within each household were combined, without reference to the area of surface sampled.

Total lead levels were measured by flame atomic absorption spectrometry (AAS) at the Mining and Materials Engineering Department, Faculty of Engineering, Prince of Songkhla University, following US EPA Method 3050 (US EPA, 1996). Prior to analysis, the dust specimens were dried at 80 °C in covered, lead-free Petri dishes in an oven for 2–6 h, sieved through a 0.85-mm nylon mesh to get rid of waste, and again dried at 80 °C for 2 h. Portions between 0.2 and 1 g were weighed and digested using concentrated nitric acid and hydrogen peroxide. Blanks were used for quality control of specimen digestion, undergoing the same treatment as the specimens. Lead concentration was determined using flame AAS (Model 905, GBC Scientific Equipment Pty. Ltd., Australia) at a wavelength of 283.3 nm. The quantitation limit of the analysis was 10 mg/kg. Precision of lead analyses was checked by running lead content standards before and after each batch of specimens and a blank was intercalated between every 10 specimens. Within-batch coefficient of variation (CV) did not exceed 2% and total CV did not exceed 5% using control samples at low, mid-range, and high concentration in the analytical range.

2.2.2. Soil specimens

Soil specimens were collected in June 2001 from the top 2 cm at the interstices of a square grid pattern (side length 70 m) superimposed on a map of the study area. At each sampling point, approximately 0.5 kg of soil was obtained using a new plastic spoon where bare soil was present. If bare soil was not present the sampling position was shifted to within 3 m, or grass and debris were removed. Specimens were stored in lead-free clear polyethylene bags until analysis. One hundred and fifty-seven soil specimens were collected in total. The analysis of lead concentration followed the same technique as for household dust specimens.

2.3. Collection of geographical variables and other independent variables

A map of the study area supplied by the local Town and Country Planning Office was used as a base map for spatial analysis using Surfer Version 8 software (Golden Software Inc., 2002). The positions of households in the study sample followed information from the local National Housing Authority Office, which provided the position of almost every house in the area, and these positions were incorporated with the base map. Where the recorded address was not included in this information, the position of the household was determined with the assistance of local health worker volunteers during home visits.

The precise location of each soil sampling point was located in the field using a combination of compass, measuring tape, calibrated-pace counting, and reference location, such as road or pathway junction, mosque, or school.

During the single visit to collect dust, an observation checklist was completed and an interview of each child's parent or guardian conducted using a structured questionnaire to obtain information regarding the occupation of household members in boat-repair work and boat-repair-related practices, details of household condition, and other potential lead contamination sources within or in the immediate surroundings of each home. All household visits were made during the daytime. Information on occupation and practices of household members included whether anyone was employed in boat repair in one of the boatyards, and, if so, whether or not equipment and/or materials used in the boat-repair yards were brought home, whether changing out of work clothes took place inside the house, the time delay between arriving home and bathing, and if and how frequently small boat repair was undertaken in the home. Household condition included construction materials and design, including the use of wood from old boats; type of water supply; and general cleanliness, as indicated by the presence or absence of obviously evident cobwebs or deposits of dust on surfaces less than 1.5 m above the floor in the main living area of the house without moving any of the furniture or fittings. Other potential lead contamination sources within or in the immediate surroundings of each home included exposed lead–acid batteries, lead sinkers for fishing nets, and lead-oxide anti-rust paint.

2.4. Data analysis

The spatial distribution of lead levels in soil and household dust was analyzed using Surfer 8.0 software. The sampling positions were first plotted on the base map and coded according to the level of lead content. As the values of environmental lead content followed a right-skewed distribution, they were logarithm transformed to produce a more symmetrical distribution before further analysis. Base-2 logarithm was used in the transformation for ease in subsequent interpretation; a unit increase in the transformed value thus represented a doubling of lead content.

The spatial dependence of lead content was explored by constructing observational semivariograms of the logarithm-transformed lead content in mg/kg of each environmental compartment, both for restricted directions and also omnidirectionally. The semivariogram is a means of representing the variance of the difference in value between all pairs of points in the data set as a function of interpoint distance, in which half the average squared difference between all pairs of data values (the semivariance) is plotted against interpoint distance. It can therefore indicate how spatial continuity changes as a function of distance and, if necessary, direction (Isaaks and Srivastava, 1989).

Best-fitting model semivariograms were selected by iteratively fitting successive models by varying the parameters and choosing the omnidirectional semivariogram that performed best in terms of the lowest absolute mean and variance of the residuals from jack-knife cross-validation by kriging among measured data points. Kriging is a means of estimating the value of a parameter at an unsampled point, using weighted linear combinations of the available data to achieve residuals having minimal mean and variance. In the jack-knife cross-validation process, each sampled point is removed in turn from the data set and its value at that point is estimated from the remaining points and compared to the observed value, thus yielding a set of residuals (Isaaks and Srivastava, 1989). Model semivariograms best fitting the observational data were then used as the basis of interpolation to construct isoline maps by kriging of soil and household dust lead throughout the study area.

To investigate the dependence of environmental lead level on distance and direction from each boatyard, linear regression modeling of logarithmically transformed lead content was undertaken. To avoid the problem of the possible influence of more than one boatyard on any position within the study area, analysis was confined to the distance and direction from the nearest boatyard, but with all boatyards incorporated into the model. In the case of soil lead, distance and direction from the nearest boatyard were the only variables included in the modeling, whereas for household dust lead a number of other variables pertaining to the household where each dust sample was taken were also included. Thus, it was possible to explore not only the effects of distance and direction from the nearest boatyard but also the possible influence of various aspects of house condition, presence of other potential sources of lead, and occupation and practices of household members in boat-repair work. The strategy adopted to identify additional household characteristics that were associated with the level of lead in household dust was to first include in the model all household variables in addition to distance and direction from the nearest boatyard, and then to selectively remove those that did not contribute significantly ($P < 0.05$) to the fit of the model as evidenced by partial F-tests, as performed by the post-estimation command, testparm, in Stata 7.0 (StataCorp, 2001).

3. Results

Dust specimens could be obtained from 238 of the 242 households. No dust was found in the remaining four households. Soil specimens were taken from 157 grid interstices. In seven dust specimens, the amount was too small to be able to perform the analysis, so that data analysis was finally performed using 231 dust and 157 soil specimens. None of the 242 households that were approached declined to participate in the study. Interviews with the guardians of children in the 242 households yielded almost complete data. Three (1.2%) were unable to give the age of their houses and 28 (11.6%) declined to give the family's income. Median monthly income among those responding was Baht 4800, with first and third quartiles of Baht 2500 and Baht 5500 (US$1 was approximately equivalent to Baht 40 at the time of the study).

3.1. *Spatial distribution of lead in soil and household dust*

The distributions of lead content of soil and household dust are presented in Fig. 2. The overall range of recorded soil lead values was wide, 1–7770 mg/kg. Fifty-one values (32%) were below the quantitation limit but were included in subsequent spatial and statistical analyses as recorded, without any imputation, as this approach has been shown to be no worse and possibly more accurate than using imputed values and certainly less biased than omitting them and using a left-censored distribution (Griffin et al., 1999; Succop et al., 2004). Approximately 85% of soil specimens had lead levels less than 150 mg/kg. Only 14 specimens (9%) had lead content equal to or greater than 400 mg/kg, which is the level above which lead in bare soil in children's play areas is considered to be a hazard according to the current residential lead hazards standards of the US EPA (2001) and which the Ministry of Industry, Thailand, has defined as polluted soil in need of treatment, and only 4.5% were above 1000 mg/kg. Nine of these 14 specimens were among the 12 specimens from sampling points that happened to fall within the perimeters of the boat-repair yards, and the highest peaks of soil lead occurred at the locations of the boat-repair yards. Several lower peaks, above 400 mg/kg, occurred at varying distances from the boat-repair yards. Elsewhere, the soil lead levels were mostly lower than 150 mg/kg (Fig. 3A).

Spherical model semivariograms fitted the soil data well, with some differences between the northern and southern parts of the study site. In these semivariograms, the semivariance was high even at the shortest interpoint distances, increased rapidly with increasing interpoint distance over a short range between 135 and 300 m, and remained high at longer interpoint distances. This pattern reflected considerable spatial variability, both within distances shorter than the minimum interpoint distance (70 m) and over larger distances. This variability is evident in the contour map of soil lead (Fig. 3B).

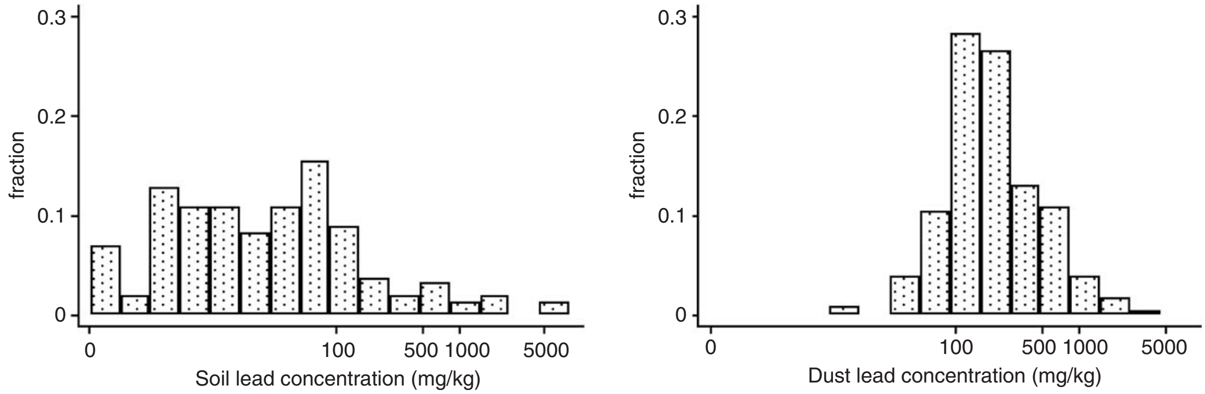

Fig. 2. Nonspatial distribution of environmental lead content on a logarithmic scale: (A) soil lead and (B) household dust lead.

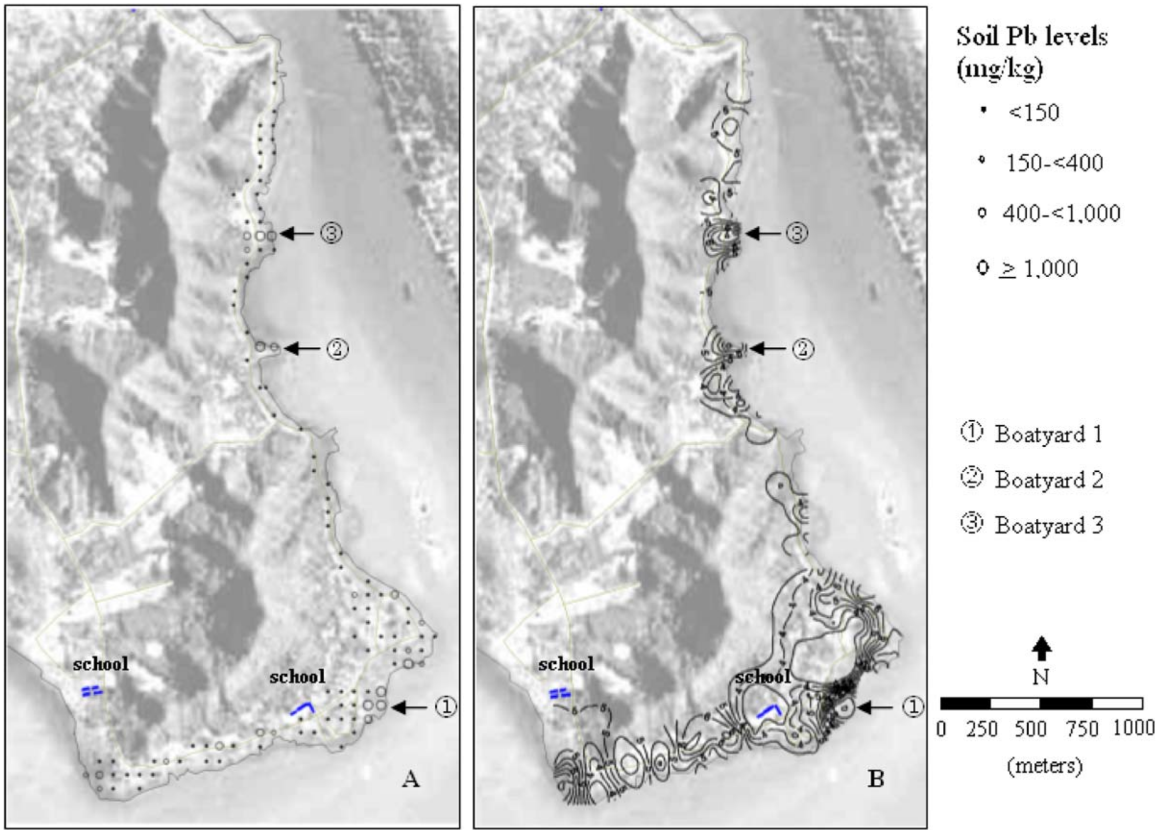

Fig. 3. Spatial distribution of soil lead levels superimposed on an aerial photograph of the study area: (A) classed post map and (B) contour map. Contours are marked in units of logarithm base-2 (soil lead in mg/kg).

Measured lead levels in household dust ranged from 10.8 to 3025.4 mg/kg, with approximately 64% of household dust specimens having lead content equal to or exceeding 150 mg/kg, 24% equal to or above 400 mg/kg, and 4.3% equal to or above 1000 mg/kg. None of the reported dust lead values was below the quantitation limit. The distribution of dust lead showed generally high levels close to each boat-repair yard and progressively lower levels at increasing distance from each yard. Nevertheless, in some areas, there were some moderately high levels interspersed among clustered low lead levels, and vice versa (Fig. 4A).

Examination of the observational semivariogram showed that the semivariance was relatively low at the minimum interpoint distance and slowly increased linearly with increasing interpoint distance, suggesting relative uniformity of dust lead levels at points close together and steadily decreasing influence with increasing distances. The smoother spatial pattern among household dust specimens compared with that of soil is seen in the contour map of dust lead (Fig. 4B).

3.2. Spatial relationship of soil and household dust lead with respect to distance and direction from the boatyards

Despite there being some evidence of spatial correlation between points that are close together, preliminary investigations of the relationship between environmental levels and distance and direction from the boat-repair yards was undertaken using linear regression.

Because the sampled area was of a long and narrow shape, direction from each boat-repair yard was modeled by dividing the area around the boatyards into two halves, each spanning 180°. However, owing to the different geographic orientations of the sampled strips in different regions, the directions were divided differently around boatyard 1 and around boatyards 2 and 3. Around boatyard 1, the main axis of the coastal strip of sampled land lay in an approximately southwest-to-northeast direction, so that sampling positions lying to the southwest of a straight line passing through the boatyard in the northwest-to-southeast direction were distinguished from those lying to the northeast of the line. Because the sampled land strip in the region of boatyards 2 and 3 had a north–south orientation, the sampling positions lying closest to these boatyards were subdivided according to whether they lay to the north or to the south of a west–east line passing through the nearest boatyard. Distance and direction from boatyards 2 and 3 were not separated because of the small number of sampling positions and similar geographical factors surrounding these two boatyards. As the dependent variable was logarithm (base-2) transformed, the coefficients for each term in the model were retransformed and expressed as multiplication factors for lead concentration in comparison with the reference

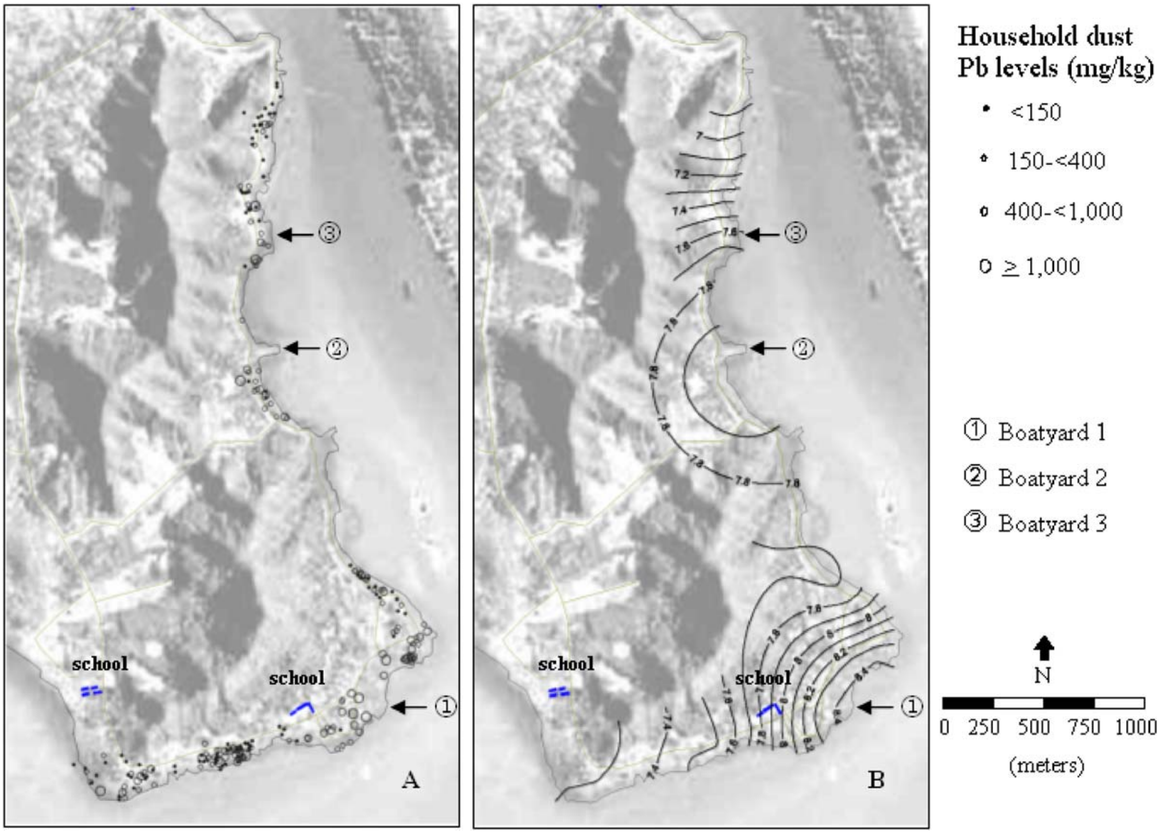

Fig. 4. Spatial distribution of household dust lead levels superimposed on an aerial photograph of the study area: (A) classed post map and (B) contour map. Contours are marked in units of logarithm base-2 (dust lead in mg/kg).

categories. The retransformation represents $e^{\beta * \ln 2}$, where β is the coefficient.

A linear regression model of soil lead levels in terms of distance and direction from the nearest boatyard failed to provide a satisfactory fit to the data, and yielded a coefficient of determination of only 0.04. No significant changes in soil lead contamination were evident among the three boatyards, or with distance and direction from the nearest boatyard.

In contrast to the very irregular distribution of soil lead, distance and direction from the nearest boatyard could explain 20% of the variation in household dust lead (Table 1, Model 1). Occupation of a household member in boat-repair work, either as a boatyard worker or as a home-based small-boat-repair worker, and house cleanliness were identified as significant predictors of household lead content. Their addition to the model containing distance and direction from the nearest boat-repair yard increased the coefficient of determination of the model to 28% (Table 1, Model 2). None of the other household variables showed any evidence of association with household dust levels.

Distance from the nearest boatyard was associated with significantly decreased dust lead levels in both directions from boatyard 1 and to the north of boatyards 2 and 3. After adjustment for the other associated factors, household dust lead levels were shown to fall off from boatyard 1 at a rate of about 7% per 100 m to the southwest and about 11% per 100 m to the northeast and from boatyards 2 and 3 at a rate of about 14% per 100 m to the north. There was no evidence of change in level of household dust lead to the south of boatyards 2 and 3. This might be a result of the additional influence of the large boatyard number 1 to the south of boatyards 2 and 3. Furthermore, the number of data points in this region was somewhat low, resulting in a wide confidence interval and consequently a less reliable estimate of the change in household dust lead level compared with other directions. Nevertheless, there were no statistically significant differences among the four directions in the change in household dust lead level with distance from the nearest boatyard.

Occupation of a household member in boat-repair work, either in boatyards or at home, was significantly associated with increases in household dust lead levels. Thirty-two of the households had at least one family member working in a boatyard and in 16 of these households home-based boat-repair was also undertaken. Another 69 households repaired boats at home but had no family member working in a boatyard, so that a total of 85 households were engaged in home-based boat-repair. The remaining 130 households were not involved in boat-repair work. Household dust lead levels were elevated by 65% (95% CI: 18–130%, $P = 0.003$) in households of boatyard workers, and by 31% (95% CI: 5–63%, $P = 0.018$) in households of

Table 1
Regression models of household dust lead levels

Factor	No. of dust specimens	Model 1 ($R^2 = 0.21$)			Model 2 ($R^2 = 0.28$)		
		MF	95% CI	*P*-value	MF	95% CI	*P*-value
Boatyard (at source)				0.048			0.390
Boatyard 1	162	1			1		
Boatyard 2	19	0.552	0.239–1.275		0.655	0.290–1.478	
Boatyard 3	50	0.498	0.287–0.866		0.685	0.393–1.193	
Direction and distance from nearest boatyard (change with distance per 100 m)							
Boatyard 1				0.000			0.003
Southwest	110	0.901	0.869–0.934		0.933	0.896–0.971	
Northeast	52	0.856	0.789–0.929		0.892	0.821–0.969	
Boatyards 2 and 3				0.002			
South	27	1.090	0.781–1.522		1.054	0.763–1.457	0.006
North	42	0.851	0.761–0.951		0.862	0.775–0.960	
Occupation							
Boat-yard worker in household/not	33/198				1.652	1.184–2.305	0.003
Small-boat repair at home/not	86/145				1.306	1.048–1.626	0.018
House cleaning							
Dirty/clean	106/125				1.281	1.037–1.581	0.022

Note: Models were constructed using logarithm base-2 (dust lead in mg/kg) as the dependent variable. MF, multiplication factor. Model 1: model with respect to direction and distance from the boatyards. Model constant = 8.86. Model 2: model with respect to direction and distance from the boatyards and other household variables. Model constant = 8.07.

small-boat-repair workers, compared with households in which no member engaged in boat-repair work. However, these increases could not be attributed to any particular practices such as keeping boat-repair equipment in the home or keeping Pb_3O_4 in the home (respectively, 40 and 33 of the 101 households with a boat repairer), a frequency of home-based repair of more than 1 boat/month (49 of the 85 households undertaking home-based boat-repair), changing work clothes in the home, or delaying bathing for over half an hour after return home from work (respectively, 13 and 14 of the 32 households with a boatyard worker).

The state of general cleanliness of the house was also a significant predictor of the level of dust lead. Those households classified in the survey as clean had a dust lead content about 22% lower ($P = 0.022$) than households classified as dirty.

4. Discussion

This cross-sectional study found a very irregular pattern of lead content in soil and an approximately exponentially declining level of lead in household dust with distance from three boat-repair yards where plumboplumbic oxide is a major component of the repair materials. In addition, it identified occupation of household members in boat-repair work and poor house cleanliness as conditions associated with elevated household dust lead.

Except for peaks of soil lead at the locations of each boat-repair yard, the soil lead levels were generally low, but showed considerable variation even over short distances. Similar variability in soil lead has been reported in the vicinity of a tetraethyllead production plant (Arrouays et al., 1996). It is likely that short-range factors exert much greater influence on the content of lead in the soil than does the spatial relationship to any of the boatyards. Short-range perturbing factors to which soil lead content may be vulnerable might include leaching from the soil during rain and disturbance by vehicles, animals, humans, etc. At the time of collection of soil specimens, the pre-rainy season (June–September) had just begun and several moderate showers had occurred in the week before collection. These could have reduced the lead content that might have accumulated during the previous 4-month dry season. On the other hand, the extreme peaks of lead content recorded for specimens taken from positions that happened to lie within each boat-repair yard may be partly explained by the lower matrix density of these specimens than of specimens taken outside the yards. The "soil" of each boatyard is actually a mixture of soil, fine wood chips, and sawdust. As the measurements of lead content were made on a weight per weight basis (mg/kg), the values would have overestimated the content of lead per unit area of ground, which might have been a more suitable parameter to reflect the contamination level.

The level of lead in household dust was very clearly linked with the minimum distance from a boat-repair yard, with an exponential fall-off in most directions fitting the data reasonably well, a pattern that is consistent with point sources of contamination. Peaks of dust lead in households at a distance from a boatyard were explained by the presence of boat-repair yard workers in the home or the actual repair of small boats in the home. Similar fall-off of household lead levels with distance have been described in areas surrounding lead smelters (Maravelias et al., 1989; Meyer et al., 1999; Trepka et al., 1997). However, other studies have mostly measured household dust lead in terms of weight of lead per unit surface area (''lead loading'') obtained from wipe, adherence, or vacuum samples (Emond et al., 1997; Harper et al., 2002; Rich et al., 1999), whereas in the current study we used the weight-per-weight content of dust lead in specimens that were collected from undisturbed positions in the household, which therefore more closely represent the average level of contamination over a prolonged period. Our rationale in using this parameter of dust lead rather than a surface lead content or a time-based rate of dust lead deposition was that, if the main source of lead was from the powdered plumboplumbic oxide used in the boatyard, then the rate of lead contamination in dust was expected to be quite variable, depending on the number of boats being repaired at any one time and the particular wind speed and direction. Furthermore, taking the specimens from a relatively undisturbed position avoided much of the ''noise'' that would have been introduced from variation in the timing and thoroughness of cleaning the house and that could have masked the average levels of contamination.

Consistent with the common method for collecting household dust specimens, dust-lead standards or guidelines have mostly been presented in terms of weight of lead per unit surface area, so that it is difficult to relate these to our own determinations of weight per weight. A closer correlation of children's blood lead with household surface dust lead loading than with dust lead concentration has been reported by several authors (Lanphear et al., 1995; Yiin et al., 2002), supporting the use of lead loading as the metric for household standards. Nevertheless, a report of the Agency for Toxic Substances and Disease Registry (ATSDR, 1988) concerning lead contamination in the United States concluded that dust levels between 500 and 1000 mg/kg begin to affect children's blood lead levels, and a dust-lead standard for London has been set at 500 mg/kg (Thornton et al., 1990), a level that some 15% of dust samples in our study area exceeded. Other studies that have reported household dust lead in terms of weight per weight have revealed wide variation, both within and across studies, and also dependent on the method used for collection of the dust. Geometric mean values for interior dust lead quoted in a review by Succop et al. (1998) for a number of communities near to ore-processing sites in the United States, ranged from 110 to 1548 mg/kg; floor dust wipe samples from homes in Jersey City, NJ, had a geometric mean of 613 mg/kg (Yiin et al., 2002), whereas vacuum cleaner dust samples from various regions of Denmark were reported to have a geometric mean lead concentration of only 9 mg/kg (Jensen, 1992). In our study, the geometric mean value of household dust lead was 210 mg/kg, which may appear low compared with many other studies. Comparisons across different settings, however, may be misleading, especially if inferences are to be drawn on the relative health risks posed. For instance, the general lifestyle of populations in the tropics, especially those in the lower socioeconomic strata as in our study area, is characterized by open-style but crowded housing and the near impossibility of maintaining a dust-free living environment. These conditions are expected to markedly increase the magnitude of human exposure to dust and thereby to lead, even at dust lead levels lower than those indicated by standards and/or guidelines from Europe or the United States.

Despite the use of weight per weight to measure dust lead content in our study to avoid some of the problems of variability in timing and thoroughness of cleaning the house, cleanliness of the house did appear to have some influence over the levels of household dust lead content. Although our classification of house cleanliness was somewhat imprecise, an attempt was made to reduce the subjectivity by having a single observer classify all households in the study and making the observations only during visits in daylight. While recent cleaning of the house could have influenced the classification of house cleanliness, regular dusting of surfaces, other than those to be used immediately for eating, and brushing of cobwebs rarely feature as regular components of housework in this society.

The large effect of occupation on household dust lead content suggested by the model suggests that boat-repair workers themselves play an important role in increasing household dust lead, probably because they either use plumboplumbic oxide at the home for repair of small wooden boats, or bring home lead dust on their clothing, skin, hair, shoes, vehicle, etc. after working at a boat-repair yard. Similar examples of take-home lead have been reported in other settings (Cook et al., 1993; Gulson et al., 1996b; Morton et al., 1982).

Comparing the respective influence of the two groups of boat-repair workers—those working at a boat-repair yard and those doing home-based repair—on household dust lead, it may at first seem surprising that the households of home-based repair workers did not have the higher elevation of household dust lead, as they actually used plumboplumbic oxide in their homes. However, the frequency of boat repair, as well as the size of the boats repaired and hence the amounts of plumboplumbic oxide used per boat, in home-based repair was far lower than for boat-repair yard workers, who, by contrast, for much of the year worked 7 days a week in close contact with plumboplumbic oxide. Observation of the work conditions revealed extensive spillage of plumboplumbic oxide on the ground and working surfaces at the boat-repair yards, as well as contamination of hands and of handles of caulking tools. While there was some variability in the behavior of boatyard workers regarding keeping boat-repair equipment and/or Pb_3O_4 in the home, their practice of bathing and changing clothes at home, and the frequency of repairing small boats at the home, we were unable to demonstrate any significant relationship between these practices and the levels of household dust lead. This may be because the small numbers of households in these subsets of the data provided insufficient statistical power to detect any associations. It is also possible that take-home lead may be occurring via pathways or behaviors for which we did not have data. As awareness of the hazards of lead contamination among the community was almost zero at the time of our study, it seems unlikely that respondents were giving what they believed were socially acceptable answers regarding their practices and thereby biasing the associations toward the null.

While the spatial distribution revealed in our study provides strong evidence for the use of plumboplumbic oxide in boat repair being a major source of lead contamination of household dust in the surrounding area, the possibility exists that there are other potential sources of lead contamination in the community. It was noted that some households kept one or two lead–acid batteries and/or large numbers of lead sinkers for fishing nets in or around the home, but there was no evidence that these were linked with elevated household dust lead levels. However, as only around 28% of the variation in household dust lead levels is accounted for in our model incorporating distance/direction form a boat-repair yard, occupation in boat repair, and house cleanliness, other factors must exist, either modifying the extent to which lead as dust enters the household or is deposited or retained in the household, or providing additional contributions to the dust lead load. The spatial pattern of household dust lead, however, is unlikely to be greatly influenced by spread from the urban center on the far side of the lagoon. The town, despite being a provincial capital, has little industry and only light traffic, as it lies at the end of a peninsula, the only through traffic being that which chooses to use a ferry to cross the lagoon rather than a much more convenient road bridge that is situated more than 10 km from the study site. In addition, leaded petrol has not been available in Thailand since 1995, 6 years before this study was undertaken. Furthermore, the pattern of decreasing household dust lead was not consistently in a direction away from the urban center or from the single road running through the study area.

In conclusion, household dust lead level is closely associated with proximity to a boatyard and occupation of household members in boat-repair work. The Department of Industrial Works, Ministry of Industry (2004), reported more than 200 boat-building and boat-repair yards throughout Thailand. Most of these use a similar process for caulking boats. Similarly to the setting in our study, many of the boatyards are located close to residential communities, which are therefore at risk of household dust lead contamination. It is recommended that in future boat-repair yards should not be established close to residential communities and that measures to reduce the spread of lead-containing dust be implemented in the boat-repair yards. The use of wooden boats is still extensive throughout many countries of south and south-east Asia. Lead contamination of the environments of coastal communities in boat-repair and boat-building districts could present a substantial public health hazard in these countries.

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References

Adgate, J.L., Weisel, C., Wang, Y., Rhoads, G.G., Lioy, P.J., 1995. Lead in house dust: relationships between exposure metrics. Environ. Res. 70, 134–147.

Agency for Toxic Substances and Disease Registry (ATSDR), 1988. The nature and extent of lead poisoning in children in the United States: a report to Congress. Atlanta, GA.

Arrouays, D., Mench, M., Amans, V., Gomez, A., 1996. Short-range variability of fallout Pb in a contaminated soil. Can. J. Soil Sci. 76, 73–81.

Arykul, S., Kooptarnon, K., 1993. Sources of Lead to the Pattani River. Department of Mining Engineering and Metallurgy, Faculty of Engineering, Prince of Songkla University, Songkhla.

Bates, M., Malcolm, M., Wyatt, R., Garrett, N., Galloway, Y., Speir, T., Read, D., 1995. Lead in children from older housing areas in the Wellington region. N.Z. Med. J. 108, 400–404.

Billick, I.H., Curran, A.S., Shier, D.R., 1980. Relation of pediatric blood lead levels to lead in gasoline. Environ. Health Perspect. 34, 213–217.

Booher, L.E., 1988. Lead exposure in a ship overhaul facility during paint removal. Am. Ind. Hyg. Assoc. J. 49, 121–127.

Cook, M., Chappell, W.R., Hoffman, R.E., Mangione, E.J., 1993. Assessment of blood lead levels in children living in a historic mining and smelting community. Am. J. Epidemiol. 137, 447–455.

Department of Industrial Works, Ministry of Industry, Thailand, 2004. Small and Medium-Sized Enterprises: Type 07501. Available at: 〈http://www.diw.go.th/diw_web/html/versionthai/data/data1.asp〉 (accessed February 2005).

Duggan, M.J., 1983. Contribution of lead in dust to children's blood lead. Environ. Health Perspect. 50, 371–381.

Emond, M.J., Lanphear, B.P., Watts, A., Eberly, S., 1997. Measurement error and its impact on the estimated relationship between dust lead and children's blood lead: members of the Rochester Lead-in-Dust Study Group. Environ. Res. 72, 82–92.

Fergusson, J.E., Schroeder, R.J., 1985. Lead in house dust of Christchurch, New Zealand: sampling, levels and sources. Sci. Total Environ. 46, 61–72.

Galvin, J., Stephenson, J., Wlodarczyk, J., Loughran, R., Waller, G., 1993. Living near a lead smelter: an environmental health risk assessment in Boolaroo and Argenton, New South Wales. Aust. J. Public Health 17, 373–378.

Garcia Vargas, G.G., Rubio Andrade, M., Del Razo, L.M., Borja Aburto, V., Vera Aguilar, E., Cebrian, M.E., 2001. Lead exposure in children living in a smelter community in region Lagunera, Mexico. J. Toxicol. Environ. Health A 62, 417–429.

Gartside, P.S., Buncher, C.R., Lerner, S., 1982. Relationship of air lead and blood lead for workers at an automobile battery factory. Int. Arch. Occup. Environ. Health 50, 1–10.

Geater, A.F., Duerrawee, M., Chompikul, J., Chairatanamanokorn, S., Pongsuwan, N., Chongsuvivatwong, V., McNeil, D., 2000. Blood lead levels among schoolchildren living in the Pattani River: two contamination scenarios? J. Environ. Med. 2, 11–16.

Golden Software Inc., 2002. Surfer, Version 8.01: Contouring and 3D Surface Mapping for Scientists and Engineers. Colorado.

Griffin, S., Marcus, A., Schulz, T., Walker, S., 1999. Calculating the interindividual geometric standard deviation for use in the integrated exposure uptake biokinetic model for lead in children. Environ. Health Perspect. 107, 481–487.

Gulson, B.L., Mizon, K.J., Korsch, M.J., Howarth, D., 1996a. Non-ore body sources are significant contributors to blood lead of some children with low to moderate lead exposure in a major lead mining community. Sci. Total Environ. 181, 223–230.

Gulson, B.L., Mizon, K.J., Korsch, M.J., Howarth, D., 1996b. Importance of monitoring family members in establishing sources and pathways of lead in blood. Sci. Total Environ. 188, 173–182.

Harper, M., Hallmark, T.S., Bartolucci, A.A., 2002. A comparison of methods and materials for the analysis of leaded wipes. J. Environ. Monit. 4, 1025–1033.

Hertzman, C., Ward, H., Ames, N., Kelly, S., Yates, C., 1991. Childhood lead exposure in Trail revisited. Can. J. Public Health 82, 385–391.

Hibbert, R., Bai, Z., Navia, J., Kammen, D.M., Zhang, J., 1999. High lead exposure resulting from pottery production in a village in Michoacan State, Mexico. J. Expos. Anal. Environ. Epidemiol. 9, 343–351.

Ibiebele, D.D., 1994. Air and blood lead levels in a battery factory. Sci. Total Environ. 152, 269–273.

Isaaks, E.H., Srivastava, R.M., 1989. An Introduction to Geostatistics. Oxford University Press, New York.

Jensen, H., 1992. Lead in household dust. Sci. Total Environ. 114, 1–6.

Jin, A., Teschke, K., Copes, R., 1997. The relationship of lead in soil to lead in blood and implications for standard setting. Sci. Total Environ. 208, 23–40.

Lanphear, B.P., Edmond, M., Jacobs, D.E., Weitzman, M., Tanner, M., Winter, N.L., Yakir, B., Eberly, S., 1995. A side-by-side comparison of dust collection methods for sampling lead-contamination house dust. Environ. Res. 68, 114–123.

Laxen, D.P., Raab, G.M., Fulton, M., 1987. Children's blood lead and exposure to lead in household dust and water—a basis for an environmental standard for lead in dust. Sci. Total Environ. 66, 235–244.

Lee, B.K., 1982. Occupational lead exposure of storage battery workers in Korea. Br. J. Ind. Med. 39, 283–289.

Lorenzana, R.M., Troast, R., Mastriano, M., Follansbee, M.H., Diamond, G.L., 2003. Lead intervention and pediatric blood lead levels at hazardous waste sites. J. Toxicol. Environ. Health A 66, 871–893.

Maravelias, C., Hatzakis, A., Katsouyanni, K., Trichopoulos, D., Koutselinis, A., Ewers, U., Brockhaus, A., 1989. Exposure to lead and cadmium of children living near a lead smelter at Lavrion, Greece. Sci. Total Environ. 84, 61–70.

Matte, T.D., Figueroa, J.P., Ostrowski, S., Burr, G., Jackson-Hunt, L., Keenlyside, R.A., Baker, E.L., 1989. Lead poisoning among household members exposed to lead–acid battery repair shops in Kingston, Jamaica. Int. J. Epidemiol. 18, 874–881.

Meyer, I., Heinrich, J., Lippold, U., 1999. Factors affecting lead, cadmium, and arsenic levels in house dust in a smelter town in eastern Germany. Environ. Res. 81, 32–44.

Morton, D.E., Saah, A.J., Silberg, S.L., Owens, W.L., Roberts, M.A., Saah, M.D., 1982. Lead absorption in children of employees in a lead-related industry. Am. J. Epidemiol. 115, 549–555.

Murgueytio, A.M., Evans, R.G., Roberts, D., 1998. Relationship between soil and dust lead in a lead mining area and blood lead levels. J. Expos. Anal. Environ. Epidemiol. 8, 173–186.

Quinn, M.J., Sherlock, J.C., 1990. The correspondence between UK "action levels" for lead in blood and in water. Food Addit. Contam. 7, 387–424.

Rahbar, M.H., White, F., Agboatwalla, M., Hozhabri, S., Luby, S., 2002. Factors associated with elevated blood lead concentrations in children in Karachi, Pakistan. Bull. WHO 80, 769–775.

Rich, D.Q., Yiin, L.M., Rhoads, G.G., Glueck, D.H., Weisel, C., Lioy, P.J., 1999. A field comparison of two methods for sampling lead in household dust. J. Expos. Anal. Environ. Epidemiol. 9, 106–112.

Spear, T.M., Svee, W., Vincent, J.H., Stanisich, N., 1998. Chemical speciation of lead dust associated with primary lead smelting. Environ. Health Perspect. 106, 565–571.

StataCorp, 2001. Stata Statistical Software: Release 7.0. Stata Corporation, College Station, TX.

Steele, M.J., Beck, B.D., Murphy, B.L., Strauss, H.S., 1990. Assessing the contribution from lead in mining wastes to blood lead. Regul. Toxicol. Pharmacol. 11, 158–190.

Succop, P., Bornshein, R., Brown, K., Tseng, C.-Y., 1998. An empirical comparison of lead exposure pathway models. Environ. Health Perspect. 106 (Suppl. 6), 1577–1583.

Succop, P., Clark, S., Chen, M., Galke, W., 2004. Imputation of data values that are less than a detection limit. J. Occup. Environ. Hyg. 1, 436–441.

Tera, O., Schwartzman, D.W., Watkins, T.R., 1985. Identification of gasoline lead in children's blood using isotopic analysis. Arch. Environ. Health 40, 120–123.

Thornton, I., Davies, D.J., Watt, J.M., Quinn, M.J., 1990. Lead exposure in young children from dust and soil in the United Kingdom. Environ. Health Perspect. 89, 55–60.

Trepka, M.J., Heinrich, J., Krause, C., Schulz, C., Lippold, U., Meyer, E., Wichmann, H.E., 1997. The internal burden of lead among children in a smelter town—a small area analysis. Environ. Res. 72, 118–130.

US EPA, 1996. Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (SW-846), third ed. EPA/SW-846. Methods 3050 National Technical Information Service, Springfield, VA.

US EPA, 2001. Residential Lead Hazard Standards—TSCA Section 403. Available at: 〈http://www.epa.gov/lead/leadhaz.htm〉 (accessed November 2005).

Yiin, L-M., Rhoads, G.G., Lioy, P.J., 2002. Seasonal influences on childhood lead exposure. Environ. Health Perspect. 108, 177–182.